ANNUAL SUMMARIES

Atlantic Hurricane Season of 1990

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ABSTRACT

The 1990 hurricane season is summarized, including accounts of individual storms. Fourteen tropical storms were tracked of which eight became hurricanes. Only one storm, Marco, hit the United States.

1. Introduction

The National Hurricane Center (NHC) identified and tracked 16 tropical cyclones in the Atlantic–Gulf of Mexico–Caribbean region during 1990, including an above-average number of tropical storms and hurricanes. Out of a total of 14 named tropical storms [maximum 1-min surface wind speed \( \geq 17 \text{ m s}^{-1} \) (34 kt)], 8 developed into hurricanes [wind speed \( \geq 33 \text{ m s}^{-1} \) (64 kt)]. These totals exceed the past 50-yr average of 9.6 tropical storms and 5.6 hurricanes. During the past 50 years, there were only two seasons with as many named storms as 1990 (1953 with 14, and 1969 with 18 including one subtropical storm). Tropical storm and hurricane tracks from 1990 are shown in Fig. 1, and additional season statistics are given in Table 1.

Although an above-average number of storms occurred, only Gustav reached category three status on the Saffir–Simpson hurricane scale (Simpson 1974). This breaks the trend of the past two years. In 1988 there were three hurricanes to reach category four or category five status, and in 1989 there were two such hurricanes.

Figure 2 shows the monthly distribution of the sum of tropical storms and hurricanes for 1990 and also of the 1944–1989 monthly averages. In this figure, the storm or hurricane was assigned to the month in which it first became a tropical storm. During 1990 there were slightly more than twice as many tropical storms and hurricanes as normal in July, August, and October; and none in June or November.

The tracks of several 1990 tropical cyclones (Cesar, Gustav, Hortense, Isidore, and Josephine) curved into higher latitudes over the central Atlantic. Steering conditions responsible for these track curvatures were associated with negative 500-mb geopotential height anomalies over large portions of the western and central Atlantic (CAC 1990a,b).

2. Individual storms

a. Tropical Storm Arthur, 22–27 July

Arthur developed from a tropical wave that crossed the coast of Africa on 18 July. The wave was upgraded to a tropical depression on 22 July based on interpretation of satellite imagery. The depression continued generally toward the west with minor fluctuations in intensity and on the 24th was upgraded to Tropical Storm Arthur, while centered about 450 km east of Trinidad. The upgrade was based on Air Force reconnaissance flight reports, as well as satellite imagery, which showed an increase in convection and banding features.

Arthur passed over the Windward Islands early on 25 July and its direction of motion shifted toward the northwest in response to the presence of an upper-level trough over the north-central Caribbean. Two reconnaissance flights on the 25th indicated that Arthur quickly strengthened to near hurricane strength after passing through the islands. A maximum surface wind speed of 36 m s\(^{-1}\) was estimated from the aircraft at 1450 UTC, and a wind speed of 45 m s\(^{-1}\) was measured at a flight-level of near 500 m a few hours later. However, because the lowest surface pressure reported was 995 mb, Arthur was kept at tropical storm strength and its best track maximum wind speed is estimated to be 31 m s\(^{-1}\).

A ship reported 18 m s\(^{-1}\) winds on this day at a location about 100 km north of the center of the storm. On the 26th, Arthur began to weaken due to increasing vertical shear and also began to be steered more towards the west by the environmental flow in lower levels of the atmosphere. It weakened to a depression on the 27th while centered about 175 km south of Hispaniola.

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Fig. 1. Tropical storm and hurricane tracks of 1990.
TABLE 1. 1990 Atlantic hurricane season statistics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Class*</th>
<th>Dates**</th>
<th>Maximum 1-min wind (m s⁻¹)</th>
<th>Minimum sea-level pressure (mb)</th>
<th>United States damage ($ millions)</th>
<th>Deaths</th>
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<tr>
<td>1</td>
<td>Arthur</td>
<td>T</td>
<td>22–27 July</td>
<td>31</td>
<td>995</td>
<td>9</td>
<td></td>
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<td>2</td>
<td>Bertha</td>
<td>H</td>
<td>24 July–2 August</td>
<td>36</td>
<td>973</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Cesar</td>
<td>T</td>
<td>31 July–7 August</td>
<td>23</td>
<td>1000</td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>4</td>
<td>Diana</td>
<td>H</td>
<td>4–9 August</td>
<td>44</td>
<td>980</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>Edouard</td>
<td>T</td>
<td>2–11 August</td>
<td>21</td>
<td>1003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Fran</td>
<td>T</td>
<td>11–14 August</td>
<td>18</td>
<td>1003</td>
<td></td>
<td></td>
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<tr>
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<td>Gustav</td>
<td>H</td>
<td>24 August–3 September</td>
<td>54</td>
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<td>28</td>
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<td>Josephine</td>
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<td>21 September–6 October</td>
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<td>3–9 October</td>
<td>36</td>
<td>985</td>
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<td>12</td>
<td>Lili</td>
<td>H</td>
<td>6–14 October</td>
<td>33</td>
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<td>14</td>
<td>Nana</td>
<td>H</td>
<td>16–21 October</td>
<td>39</td>
<td>989</td>
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<td></td>
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</table>

* T: tropical storm, wind speed 17–32 m s⁻¹ (34–63 kt). H: hurricane, wind speed 33 m s⁻¹ (64 kt) or higher.
** Dates begin at 0000 UTC and include tropical depression stage.

The depression momentarily fluctuated in strength as deep convection temporarily reformed after its low-level circulation, but Air Force reconnaissance and satellite imagery indicated that the system degenerated to an open wave by late on the 27th.

Tropical storm warnings were issued for the Windward Islands approximately 10–16 h before the center moved through the area. There were no official reports of sustained tropical storm force wind speeds. However, 19 m s⁻¹ winds for several minutes were reported at Trinidad during a telephone call with the National Hurricane Center. The warnings issued for Puerto Rico and Hispaniola turned out to be unnecessary.

b. Hurricane Bertha, 24 July–2 August

Bertha was an Atlantic hurricane that originated from a nontropical area of low pressure near Cape Hatteras, North Carolina. The “Hatteras low” was detected on 24 July moving southeastward. By the 25th,
the low began recurving southwestward toward Florida. A postanalysis (not shown) indicates that this system became a tropical depression while centered about 550 km east of Daytona Beach, Florida, on the 27th. The depression drifted southwestward and made a counterclockwise loop about 450\(^1\) km east-northeast of Cape Canaveral, Florida. Based on 18 m s\(^{-1}\) sustained winds reported by a Russian ship, the depression was deemed to have reached tropical storm strength early on 28 July.

Air Force reconnaissance reports indicated Bertha reached hurricane strength early on the 29th while centered about 850 km west-southwest of Bermuda. Hurricane Bertha experienced strong shearing while continuing northeastward and weakened to a tropical storm later on the 29th, with the center displaced from the convection. However, Bertha became a hurricane again on the 30th, while centered 415 km northwest of Bermuda. An Air Force reconnaissance plane at 1102 UTC found 41 m s\(^{-1}\) winds at an altitude of 500 m with a surface pressure of 988 mb.

Hurricane Bertha, with an increasing expanse of tropical storm force winds, continued moving northeastward as the ridge to the north eroded. The system began accelerating on 1 August and the center passed just west of Sable Island late on that day. Maximum sustained surface winds of 36 m s\(^{-1}\) and a minimum central pressure of 973 mb measured by reconnaissance aircraft occurred early on 2 August. Bertha was declared extratropical later on 2d with the center directly over Sydney, Nova Scotia, at that time. The weakening extratropical system continued northward over the eastern Gulf of St. Lawrence.

For most of its life, Bertha was primarily of concern to the marine community with numerous ships reporting sustained winds in the 18–26 m s\(^{-1}\) range. A moored buoy located at 41.1\(^{\circ}\)N, 61.1\(^{\circ}\)W reported 29 m s\(^{-1}\) winds, with a significant wave height of 7.6 m and a maximum wave height of 15.2 m on the 1st. The broad circulation also produced high surf along the Atlantic coast from Nova Scotia to North Carolina. Moderate beach erosion occurred along the coast of North Carolina and the Outer Banks.

Bertha produced copious rainfall over Nova Scotia with storm totals in excess of 178 mm at Hunters Mountain and at Braddeck, Nova Scotia. A total of nine people perished as a result of Bertha. Waves of 9 m, whipped by winds gusting to 40 m s\(^{-1}\), snapped the keel of the 181-m Greek freighter *Corazon*. Six crew members of the *Corazon* perished while trying to abandon ship, and one seaman was swept off the 73-m container ship *Patricia Star* while attempting to secure a deck load in heavy seas. Bertha was also blamed for rip currents that drowned two people at north Florida beaches.

c. *Tropical Storm Cesar, 31 July–7 August*

Cesar developed from a tropical wave that moved off the northwest coast of Africa on 29 July and became a tropical depression on the 31st, while centered about 550 km south of the Cape Verde Islands. The depression moved west-northwestward and was upgraded to Tropical Storm Cesar on 2 August. Based on satellite intensity estimates, a minimum central pressure of 1000 mb and maximum sustained winds of 23 m s\(^{-1}\) were maintained from 2 August to 5 August. The storm turned more toward the northwest on the 4th and in response to a weakness in the subtropical ridge to the north of the storm. Cesar became nearly stationary on the 6th and was downgraded to tropical depression status as the low-level center separated from the deep convection in response to an increase in upper-level shear from the southwest. The depression dissipated on the 7th when the remnants were located about 2000 km east-southeast of Bermuda.

d. *Hurricane Diana, 4–9 August*

1) *Synoptic History*

Diana formed from a well-defined tropical wave that moved off Africa on 27 July and represented a typical example of developing disturbances over the Atlantic basin. The wave moved through the southern Windward Islands with a marked wind shift and an area of about 3.5-mb 24-h pressure falls. The wave had its maximum amplitude at the midlevels and was accompanied by a strong upper-level anticyclone, as reflected in upper-air data from the Lesser Antilles.

The first Air Force reconnaissance mission in this system investigated the wave when it was over the extreme southeastern Caribbean and found squalls but no low-level circulation. Satellite pictures suggested that the system continued to be accompanied by a large area of thunderstorms, with the most active area of convection moving along the South American coast directly over the Netherland Antilles. On 4 August, high-resolution satellite images indicated cyclonic rotation in the low clouds and deep convection covering a large portion of the western Caribbean, suggesting that a tropical depression was forming near the eastern tip of Honduras. That was confirmed by limited surface observations and by an Air Force plane, which found an incipient 1008-mb center later that day.

The depression rapidly reached tropical storm intensity while moving northwestward, under the influence of a midlevel pressure trough in the Gulf of Mexico. Diana crossed the Yucatan Peninsula and then took a more westerly track as the trough of low pressure in the Gulf weakened. Diana continued to intensify...
and reached category 2 hurricane status on 7 August near 95°W prior to landfall near Tuxpan, Mexico. Figure 3 shows a satellite picture of the hurricane just prior to the hurricane’s final landfall. After moving inland, Diana was declared dissipated by 1200 UTC on 8 August over western Mexico. However, a post-storm analysis indicated that Diana continued westward as a low pressure area with some convection until 1200 UTC 9 August, when it dissipated over the eastern Pacific, near Puerto Vallarta, Mexico.

2) METEOROLOGICAL STATISTICS

In addition to constant satellite surveillance, there were four Air Force reconnaissance missions after the system was declared a tropical depression. Daily investigative flights were flown while the system traveled over the Caribbean as a strong tropical wave. The first Air Force reconnaissance fix reported 1003 mb and a maximum flight-level wind of 23 m s⁻¹ northeast of the center on 5 August when the system was in the Gulf of Honduras. Ship observations over the northwest Caribbean indicated that Diana was becoming better organized and that the storm had a large circulation. A ship traveling from Puerto Cortes, Honduras, to Las Minas, Panama, reported 15–18 m s⁻¹ winds, 2.4-m swells from the east-southeast, and numerous showers and thunderstorms on 5 August when Diana was in its developing stage. Merida, on the northwest tip of Yucatan, reported sustained winds of 15 m s⁻¹ with gusts to 18 m s⁻¹ and heavy rain for several hours on 6 August, as the storm passed south of that location.

Diana strengthened rapidly after moving away from the Yucatan Peninsula into the Bay of Campeche. A reconnaissance aircraft measured a surface pressure of 986 mb late on 7 August and flight-level winds as high as 57 m s⁻¹. However, the postanalysis best track minimum surface pressure and maximum 1-min surface wind for Diana are estimated at 980 mb and 44 m s⁻¹ at 1800 UTC 7 August.

3) WARNINGS

Tropical storm warnings were issued for portions of Belize and the Yucatan Peninsula and hurricane/tropical storm warnings were issued from La Pesca to Lerdo de Tejada, Mexico.

4) CASUALTY AND DAMAGE STATISTICS

Based on an unofficial report from an amateur radio operator, the total number of deaths associated with Diana is 96. The hurricane caused extensive damage to property, agriculture, and roads in mountainous areas in the states of Hidalgo and northern Veracruz. Most of the damage was produced by torrential rains, which triggered mudslides and flooding. The coastal town of Tamiahua was directly hit by the hurricane.

Fig. 3. High-resolution GOES image of Hurricane Diana at 1701 UTC 7 August 1990, as the ragged eye approached the Mexican coast near Tuxpan.
e. Tropical Storm Edouard, 2–11 August

Edouard began on 2 August over the far northeast Atlantic as a wave on a cold front. Within the next 24 h, the wave developed into a strong midlatitude cyclone over sea surface temperatures of 22°C. The nontropical storm drifted northward on 3 August and began to weaken slightly on the 4th as it turned toward the southwest and moved across the Azores. Heavy rains and gusty winds of 10–15 m s⁻¹ were reported at the islands on the 4th. From the 6th through the morning of the 8th, the system made a counterclockwise loop while located between 370 and 550 km to the southwest of the Azores. During this time, deep convection became better organized near the center of the circulation, and the system was designated a tropical depression late on the 6th.

Based on satellite and ship data, the depression strengthened to tropical storm strength late on the 8th and began moving toward the northeast. Maximum sustained winds of 21 m s⁻¹ and a minimum central pressure of 1003 mb occurred on the 9th. Lajes Air Force Base on the island of Terceira, Azores, reported surface wind gusts of 20 m s⁻¹, although sustained winds of 23 m s⁻¹ with gusts to 31 m s⁻¹ were recorded on a 127-m tower. Strong shearing from the southwest stripped the storm of its convection by the 10th, and the system was downgraded to a tropical depression later on this day and was declared extratropical on the 11th. The extratropical low pressure center with winds of 10–15 m s⁻¹, continued toward the east and dissipated near the coast of Portugal on the 13th.

g. Tropical Storm Fran, 11–14 August

A low-latitude tropical wave moved from Africa into the eastern Atlantic on 9 August and was upgraded to a tropical depression on the 11th. The depression was embedded in strong, deep easterlies and moved quickly westward across the tropical Atlantic, remaining south of 10°N. By late on the 12th the system had become “too weak to classify” using the Dvorak (1984) tropical cyclone classification technique and was downgraded to an open tropical wave.

On the 13th, the system again became better organized and was upgraded to Tropical Storm Fran later on that date based on a wind report from a ship. Tropical storm warnings were subsequently issued for the extreme southern Windward Islands late on the 13th. Trinidad reported a sustained wind of 18 m s⁻¹ and a surface pressure 1005 mb on the 14th as the storm center passed over the island. The storm was small when it moved across the extreme southern Windward Islands and, with half its circulation over Venezuela, dissipated late on the 14th.

h. Hurricane Gustav, 24 August–3 September

The tropical wave that spawned Gustav moved off the northwest coast of Africa on 18 August. The system became embedded within the intertropical convergence zone (ITCZ) on its westward journey across the tropical Atlantic and did not begin strengthening until late on the 23rd and early on the 24th. It is estimated that the system became a tropical depression about 1500 km east of Barbados on 24 August.

The tropical depression gradually strengthened while moving west to west-northwest near 5 m s⁻¹ and, based on an analysis of satellite imagery, reached tropical storm strength about 1100 km east of Barbados on the 25th.

There was some concern that a cold low located to the northwest of Gustav would inhibit development during the next day or so. However, the low had little impact. Gustav reached hurricane strength 450 km east-northeast of Barbados on the 26th. The first reconnaissance aircraft fix in Gustav had 33 m s⁻¹ winds at the 500-m flight level with 36 m s⁻¹ winds estimated at the surface at 1217 UTC on the 26th.

A hurricane watch was issued soon thereafter for the northern Lesser Antilles, and a portion of that area was placed under hurricane warnings at 2200 UTC on the 26th. However, the ridge to the north was breaking down, and Gustav responded by taking a gradual northwestward and then northward turn with the center of the system bypassing the Lesser Antilles 330 km to the east. Figure 4 shows Gustav centered well to the southeast of Bermuda. Aircraft reconnaissance reports indicated that Gustav reached its minimum central pressure of 956 mb with maximum sustained winds of 54 m s⁻¹ near 0600 UTC 31 August, while centered about 700 km east-southeast of Bermuda.

Late on the 31st, an upper trough to the west of the system imparted a northeastward motion to Gustav, and on 1 September Gustav began merging and interacting with a frontal zone to the north. This interaction also coincided with Gustav beginning to weaken. The Galion, a vessel of French registry, appears to have gone through or near the edge of the eye with 36 m s⁻¹ winds reported on the 2d. Gustav began losing tropical characteristics while accelerating toward the northeast on the 3d and was declared extratropical on that day. Meteosat imagery showed that the remnants of Gustav passed within 400 km to the south of Iceland.

Figure 5 shows an example of data used by the NHC to prepare hurricane advisories in Gustav and other tropical cyclones during 1990. One of the required parameters in marine advisories is the radius from the tropical cyclone center of 18 m s⁻¹ surface wind speeds. The 18 m s⁻¹ threshold marks the onset of tropical storm conditions and is a critical parameter for maritime interests in specifying tropical cyclone watches and warnings and in evacuation planning. To help estimate the horizontal distribution of wind speeds, data is processed and analyzed from the Special Sensor Microwave Imager (SSM/I) aboard the Defense Meteorological Satellite Program’s (DMSP) Block 5D-2 F8 polar-orbiting satellite (Hollinger 1989). The wind speeds over the ocean were estimated from upwelling
radiation measured by SSM/I sensors at several microwave frequencies. Unfortunately, both surface wind effects and atmospheric moisture (especially rain) contribute to the upwelling radiation. This greatly complicates interpreting the result of the wind speed calculation. To simplify the interpretation, screening criteria and “rain flags” are employed (Goodberlet 1989) to estimate the degree of uncertainty of each calculated wind speed due to the presence of intervening moisture. The data in Fig. 5 (Rappaport 1990) shows the wind speed and rain-rate pattern for Hurricane Gustav, derived from SSM/I data, near 1100 UTC 31 August when the system was centered at about 31.5°N, 57°W.

h. Tropical Storm Hortense, 25–31 August

The seedling for Hortense was a tropical wave that emerged from the northwest coast of Africa on 21 August. Curved convective bands visible in satellite imagery suggested a cyclonic circulation, and the system was declared a tropical depression on the 25th after ship reports confirmed that the circulation was on the surface. The depression was about 1500 km east of the developing Tropical Storm Gustav at this time.

The tropical depression initially moved on a west-northwestward track. The upper-level outflow became better established and the system became Tropical Storm Hortense about midway between the Cape Verde Islands and the Lesser Antilles on the 26th. On that day, an upper-level low pressure area turned the storm more toward the north and also provided enough shear to slow development. As the upper low opened into a trough and moved eastward, its impact on Hortense diminished and the tropical storm resumed a general northwestward track. Gradual strengthening continued and an estimated minimum central pressure of 993 mb and a corresponding maximum sustained wind speed of 28 m s⁻¹ occurred on the 28th.

By 29 August, Gustav had strengthened to a hurricane. The upper-level outflow from Gustav overspread Hortense, providing sufficiently strong shear to weaken Hortense to a tropical depression on the 30th. The depression turned more toward the north and dissipated on the 31st about 1300 km east-northeast of Bermuda.

i. Hurricane Isidore, 4–17 September

Isidore developed from a vigorous tropical wave that moved off the African coast on 3 September. Due to the time of the year and the location, it appeared for a while that the system was going to be a typical westward-moving Cape Verde hurricane. However, the steering flow associated with a persistent midlevel trough in the central Atlantic caused the storm to move in a general north-northwest course over open waters.

Based on analysis of satellite imagery indicating a large and well-defined low-level circulation with deep convection, the wave developed into a tropical depression on 4 September. The system strengthened steadily
to a tropical storm on the 5th and to a hurricane on the 7th. Based on satellite estimates, Hurricane Isidore reached its maximum intensity on the 7th at 1200 UTC with maximum sustained winds of 44 m s⁻¹ and a minimum central pressure of 978 mb.

As the hurricane moved on a general north-northwest course it encountered strong upper-level winds induced by the same trough that was steering the hurricane north-northwestward. Due to the strong shearing Isidore was downgraded to tropical storm status on the 8th. However, an upper low developed within the trough and moved southward, producing a favorable environment for Isidore to reintensify. As the shear relaxed, an eye developed within a circular mass of convection, and once again the system was upgraded to a hurricane. It moved over cooler waters and weakened several days later.

While Isidore moved generally north-northwestward, the hurricane track had several minor meanders. Isidore was absorbed by a large extratropical low on 17 September north of 50°N.

j. Hurricane Josephine, 21 September–6 October

Josephine originated from a tropical wave that moved off the African coast on 16 September and became a tropical depression on the 21st. The depression immediately turned northward in response to a deep low over the northeast Atlantic. During the next few days the surface low over the northeast Atlantic weakened and by the 24th surface high pressure began building to the north of the depression, from the west. The depression then turned toward the west and strengthened to a tropical storm. A strong upper-level trough located to the northwest produced shearing over the storm on the 25th and Josephine weakened to depression strength on the 26th.

By 28 September, a broad, weak trough located over...
the northwest Atlantic caused the depression to turn toward the northwest, and Tropical Depression Josephine spent the next two days moving toward the weakness in the pressure field. By the 30th, the trough had moved eastward and Josephine turned toward the north and northeast into the wake of the weak eastward-moving trough. The trough was too weak to capture the depression, and by 2 October the next high pressure center that had moved off the Canadian Maritimes began to block Josephine’s escape to the northeast. Josephine reintensified to tropical storm strength as the high pressure forced the storm into a 360° clockwise turn during the following three days.

By 4 October a vigorous frontal trough had moved off the northeastern United States coastline into the north-central Atlantic. Tropical Storm Josephine, located in a favorable upper-outflow pattern, strengthened to hurricane force at 0000 UTC 5 October as it began to move toward the northeast in advance of the frontal trough. However, by the 5th, a frontal wave began to form in the trough just to the north of Josephine. The hurricane tracked around the eastern periphery of the large developing midlatitude storm on the 5th. The lowest satellite-estimated pressure of Josephine was 980 mb with associated winds of 39 m s⁻¹ at 1800 UTC 5 October. On the 6th, Josephine became an extratropical low pressure center as it continued to move northward to the east of the midlatitude storm. The newly formed midlatitude storm later developed tropical characteristics and became Hurricane Lili.

k. Hurricane Klaus, 3–9 October

Klaus originated from a tropical wave that moved off the coast of Africa on 27 September. The wave moved across the Atlantic for several days while occasionally showing signs of developing and finally became a tropical depression when centered about 185 km east of Dominica in the Lesser Antilles on 3 October. The system drifted slowly toward the northwest for three days, caught in a weak steering current. It quickly strengthened to a tropical storm at 1800 UTC on the 3d and reached hurricane strength at 1200 UTC on the 5th. At this time, the center was at its point of closest approach to the Leeward Islands and was only about 45 km east of Antigua and, shortly thereafter, about 20 km east of Barbuda.

Klaus reached its peak intensity (based on reconnaissance data) at 1200 UTC 5 October with maximum sustained winds of 36 m s⁻¹ and minimum central pressure of 985 mb. Although Klaus moved close to the Leeward Islands as a hurricane, there were no observations of sustained tropical storm force winds at nearby islands. This was due to the frequent shearing conditions that caused most of the deep convection and strong winds to be located north and east of the circulation center.

On the 6th, Klaus weakened to a tropical storm and turned slightly toward the west-northwest, its center remaining rather close to the northern Leeward Islands and then the United States and British Virgin Islands. Early on the 8th, Klaus was north of the Mona Passage when it weakened to a tropical depression in response to persistent strong shearing.

Klaus regained deep convection near its center and also regained tropical storm status later on the 8th as it turned more toward the northwest. There were several ship reports with sustained wind speeds of tropical storm force. All but a few of these were well removed from the circulation center and were more closely associated with a strong pressure gradient. The highest wind report from a ship was 24 m s⁻¹ at 1500 UTC on the 8th, located 150 km northeast of the center.

By midday on the 8th, a secondary low pressure center was noted at midatmospheric levels over eastern Cuba. This low drifted westward and gradually worked its way to the surface. By 1800 UTC on the 9th, Klaus had dissipated and this new low became the dominant feature that eventually developed into Tropical Storm Marco. The remnants of Klaus, interacting with Marco and a slowly moving frontal trough, were responsible for heavy rainfall that spread across portions of the southeastern United States. Four drowning deaths related to the remnants of Klaus were reported to have occurred in South Carolina when a dam burst and swept away a car and its occupants. In addition, seven deaths were confirmed on the Caribbean island of Martinique and were associated with heavy rains from Klaus.

Tropical storm warnings associated with Klaus were issued for portions of the Leeward Islands as well as for the central and northern Bahamas, and hurricane warnings were issued for the extreme northeast Caribbean islands from St. Martin to Antigua.

l. Hurricane Lili, 6–14 October

While Hurricane Josephine was moving cyclonically around a cold low aloft several hundred miles southwest of the Azores on 5 and 6 October, the cold low was working its way down to the surface. There were indications that the low had reached the surface by 0600 UTC on the 6th when the Dutch ship Wiron II reported southwest winds of 21 m s⁻¹ and a pressure of 1004.0 mb at a position 110 km southeast of the new low pressure center. Thus, the new system was already a subtropical storm at that time. The German merchant ship Fichtelberg reported winds of 26 m s⁻¹ 335 km west-northwest of the center at 1200 UTC on the 6th and at 1500 UTC on the 8th, and the M.T. Kristhild reported a pressure of 998 mb with winds of 27 m s⁻¹ 335 km north-northwest of the center. The fact that the strongest winds were well removed from the center indicated that the system was still subtropical.

Satellite imagery indicated that the system gradually acquired tropical characteristics during the next few
days and became Hurricane Lili on the 11th with a
minimum central pressure of 987 mb and maximum
sustained winds of 33 m s⁻¹. Lili moved just south of
due west at a rapid forward speed of 10 to 13 m s⁻¹
on this day in response to strong ridging to the north
and lower pressure to the south. On that course,
the center passed 225 km to the south of Bermuda about
2100 UTC on the 11th, just prior to the first Air Force
reconnaissance fix.

Reconnaissance estimates of surface pressure varied
only slightly during the next two to three days as the
forward speed of Lili reduced to 6 m s⁻¹ during the
process of recurving around the southwestern portion
of the high pressure area, then centered over New-
foundland. On the 13th, Lili weakened to a tropical
storm as the center passed within 315 km to the east-
seast of Cape Hatteras, North Carolina. The New-
foundland high moved southeastward and the steering
currents around the high imparted a northeast motion
to Lili, away from the United States. Lili’s forward
motion accelerated as it moved northeastward, and the
storm was moving in excess of 18 m s⁻¹ when it skirted
Nova Scotia as an extratropical storm and passed over
the extreme southeastern portion of Newfoundland.

Early on 12 October when Lili was moving rapidly
toward the west, some model guidance indicated that
the hurricane would continue moving westward at a
rapid rate and move inland over North Carolina. Other
guidance indicated the forward motion would decrease
and the hurricane would recurve, brushing the Outer
Banks of North Carolina, and miss most of the United
States east coast. However, by the morning of the 12th,
the hurricane had not shown any dramatic decrease in
forward speed, and conservative projections indicated
that the center could be near the Outer Banks of North
Carolina by daybreak on the 13th. Official forecasts
continued to indicate that Lili would likely recurve
slightly east of the Outer Banks and would not
strength beyond a category 1 hurricane on the Saffir–
Simpson scale. The strength factor meant that no mas-

tive evacuations would be required even if the center
passed over the Outer Banks. However, with daylight
hours for preparation running out, it was decided at
1600 UTC on the 12th to issue a hurricane warning
for the easternmost coast of North Carolina northward
to Virginia Beach, Virginia. Shortly after the warnings
were issued, reconnaissance reports indicated the ex-
pected slowdown in forward speed was starting to take
place along with a turn to the northwest. Those ob-
servations increased the confidence in the “official fore-
cast,” which continued to call for the center to pass
just to the east of the Outer Banks of North Carolina.
Also, all the strong winds were north and east of the
center. This meant that the North Carolina and Vir-
ginia coasts, being on the fringe of the weak side, would
not experience hurricane conditions. Those develop-
ments led to the hurricane warnings being changed to
tropical storm warnings 3 h after the hurricane warn-
ings were issued.

m. Tropical Storm Marco, 9–12 October

1) SYNOPSTIC HISTORY

Early on 9 October, Tropical Storm Klaus was lo-
cated east of the Bahamas, moving northwestward, and
becoming poorly organized. At the same time, a cold
low aloft was developing over Cuba. By 1200 UTC 9
October, Klaus was dissipating and the new low was
developing downward to the surface over central Cuba.
This new low was designated Tropical Depression Fif-
teen near Cabarien, Cuba.

The depression moved west-northwestward along the
north coast of Cuba and then turned toward the north-
west over the Florida Straits. The system became
Tropical Storm Marco at 0600 UTC 10 October while
centered about 55 km south-southwest of Key West, Florida.
After passing midway between the Dry Tor-
gugas and Key West, Marco moved generally toward
the north at near 5 m s⁻¹ just off the Florida west coast.
The storm reached its peak intensity near 0600 UTC
11 October with 28 m s⁻¹ sustained winds and a 989-
mb central pressure. The center moved to just a few
kilometers west of Bradenton Beach by 1200 UTC 11
October and continued hugging the coast, with much of
its circulation over land in the St. Petersburg area,
moving to near Clearwater around 1500 UTC.

Marco was downgraded to a tropical depression at
0000 UTC 12 October just offshore of Cedar Key,
Florida. The central pressure rose as the center of the
depression moved inland, and the system was declared
extratropical at 1200 UTC over central Georgia. The
low could be followed in surface pressure and wind
reports for another 24 h, moving through Georgia and
into South Carolina. The weakening low was finally
absorbed by a frontal system in the vicinity of Colum-
bia, South Carolina, near 1200 UTC 13 October.

Although Marco brought sustained tropical storm
force winds to several areas on the Gulf of Mexico side
of the Florida peninsula and to the Florida Keys, the
storm and its remnants will also be remembered for
contributing to heavy rains previously initiated by the
remnants of Klaus over Georgia and the Carolinas.

2) METEOROLOGICAL STATISTICS

There were five aircraft reconnaissance missions into
Marco with a total of 27 center fixes during a 42-h
period from the time Marco was in the Florida Straits
until moving onshore near Cedar Key. The best-track
peak wind of 28 m s⁻¹ on the 11th is based on an
aircraft measurement of 32 m s⁻¹ at 500 m. The highest
intensity estimate from satellite imagery during this
time was also 28 m s⁻¹.

The lowest central pressure reported by Air Force
reconnaissance aircraft was 989 mb at 0816 UTC 11
October, while the lowest pressure reported over land
was 992.4 mb at 0857 UTC. The land report came
from an observer on Lido Key, just west of Sarasota,
with a barometer that had been calibrated at the At-
lantic Oceanographic and Meteorological Laboratory’s Hurricane Research Division a week earlier.

Although Marco was downgraded to a tropical depression just prior to making final landfall in the vicinity of Cedar Key, and although all the aircraft reconnaissance center fixes of Marco during the tropical storm stage reported the actual center remaining over water, Marco will be counted as a United States “hit” since much of the inner circulation was actually over the St. Petersburg area at one time. This is consistent with an adaptation of the definition of a direct hit found in Hebert and Case (1990). Using $R$ as the radius of maximum winds in a tropical cyclone (the distance in kilometers from the storm’s center to the circle of

### Table 2. Tropical Storm Marco selected surface observations, October 1990.

<table>
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<tr>
<th>Location</th>
<th>Minimum sea-level pressure</th>
<th>Maximum surface wind speed</th>
<th>Storm surge (tide height above normal)</th>
<th>Rain (storm total)</th>
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<td>10/010</td>
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* Time of 1-min wind speed unless only gust is given.
maximum winds around the center), all or parts of counties falling within approximately 2R to the right and R to the left of a storm's center were considered to have received a direct hit. (This assumes the observer is at the storm center and is looking toward the direction of motion.) In addition, the weather officer on-board one of the Air Force missions flying Marco reported that she could see land while in the center, making a fix just offshore Sarasota. It is interesting to note that the last year the United States went without a hit from a tropical storm or hurricane was 1890 (Neumann et al. 1990).

Table 2 lists selected surface observations associated with Marco. Several reports of sustained tropical storm force winds are noted along the west coast of the Florida peninsula and the Florida Keys, while the highest reported gusts reached 38 m s⁻¹ at the Sunshine Skyway Bridge across Tampa Bay and also at Bradenton located just south of Tampa Bay. The U.S. Coast Guard Cutter Steadfast reported 23 m s⁻¹ sustained winds with gusts to 26 m s⁻¹ while docked at the Coast Guard station in St. Petersburg. There were four tornadoes reported in Florida; one each in Sarasota County, Sumter County, near the Citrus-Levy county line, and near Lake City in Columbia County.

The largest rainfall in Florida associated with Marco was near 150 mm along the west-central Florida coast. The moisture from Marco continued spreading northward over the eastern United States, and very large rainfall totals were reported in Georgia, South Carolina, and North Carolina, associated with a combination of the remnants of Marco, a slow-moving frontal system, and residual moisture from the remnants of Klaus. Several amounts of 150 to 330 mm were reported in Georgia, South Carolina, and North Carolina. The largest rainfall total reported in Georgia was 505 mm at Louisville, in Jefferson County, 55 km southwest of Augusta from 2200 UTC 9 October to 2200 UTC 12 October. Louisville also reported the largest 24-h rainfall (from 2000 UTC 11 October to 2000 UTC 12 October), with 417 mm. Rainfall of 50 to 125 mm, associated with the remnants of Marco, also spread over portions of northwest Virginia, western Maryland, the eastern panhandle of West Virginia and the Susquehanna Valley of Pennsylvania. Although considerable flooding occurred due to these heavy rains, some of the rainfall was considered beneficial since it followed a prolonged dry spell.

The highest reported storm-surge values from the Florida west coast were 0.8 m above-normal astronomical tides on Sanibel Island and near 0.6 m at Port Charlotte, Anna Maria Key, and the Franklin Locks in Fort Myers.

Beach erosion was mostly minor on the Florida west coast from Collier to Pinellas County and on the Florida east coast from Indian River to Nassau County.

3) WARNINGS

Tropical storm warnings were posted from the Florida Keys northward along the entire west coast of the Florida peninsula to Apalachicola. Most of this area received tropical storm force winds except for the extreme northern portion in the vicinity of Apalachee Bay where the winds remained offshore.

A tropical storm warning was also posted for the east coast of the Florida peninsula from Vero Beach northward to Fernandina Beach. The effects of Marco on the east coast were somewhat anticlimactic since slightly higher wind speeds were recorded during each of the two days prior to the development of Marco. These winds were due to the large-scale pressure gradient from the remnants of Klaus and high pressure centered off the mid-Atlantic coast.

4) CASUALTY AND DAMAGE STATISTICS

A total of seven drowning deaths are attributed to Marco, with four in Georgia, one in South Carolina, and two in North Carolina.

Although no deaths were attributed to Marco in Florida, the Card Sound Road in the Florida Keys, the Highway 776 bridge in Charlotte County, Siesta Key roads in Sarasota County, several homes in Manatee County, U.S. Highway 41 in Hillsborough County, and U.S. Highway 19 in Citrus County were flooded.

The total damage estimate is $57 million. Almost all damage occurred from the flooding produced by the heavy rains, including rains from the remnants of Klaus as well as Marco. Damage estimates include

<table>
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<th>Forecast period (h)</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>72</th>
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<td>30</td>
<td>104</td>
<td>191</td>
<td>276</td>
<td>360</td>
<td>567</td>
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<tr>
<td>(Number of cases)</td>
<td>269</td>
<td>(243)</td>
<td>(215)</td>
<td>(187)</td>
<td>(163)</td>
<td>(121)</td>
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<tr>
<td>1980–1989 average</td>
<td>33</td>
<td>106</td>
<td>206</td>
<td>—</td>
<td>417</td>
<td>636</td>
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<tr>
<td>1990 departure from 1980–1989 average</td>
<td>— 11%</td>
<td>— 2%</td>
<td>— 7%</td>
<td>—</td>
<td>— 14%</td>
<td>— 11%</td>
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<tr>
<td>1990 range</td>
<td>0–198</td>
<td>0–511</td>
<td>9–671</td>
<td>9–953</td>
<td>9–1281</td>
<td>52–1749</td>
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n. Hurricane Nana, 16–21 October

The 14th named system of the 1990 Atlantic season developed from a vigorous tropical wave that moved over the Cape Verde Islands on 7 October. The wave traveled westward for several days and, based on satellite images and data from an Air Force reconnaissance plane, became a tropical depression about 650 km northeast of Puerto Rico on the 16th. The depression intensified rapidly and reached hurricane status at 1800 UTC on the 17th after turning toward the north-northeast. Nana reached a minimum central pressure of 989 mb with maximum sustained winds of 39 m s\(^{-1}\) on the 19th and posed a brief threat to Bermuda. However, an impulse of upper-level westerlies moved across the hurricane and separated the convection from its low-level center. Consequently, Nana weakened to a tropical depression and drifted in a southerly direction, steered by the low-level flow until it dissipated on the 21st.

3. Verification

The NHC issues "official forecasts" of the center position and maximum 1-min wind speed for all tropical cyclones in the Atlantic, Caribbean, and Gulf of Mexico. These forecasts are issued at 6-h intervals, for the periods of 12, 24, 36, 48, and 72 h. After the season, these forecasts are verified by comparison with the "best track" postanalysis of all available data. Table 3 lists the official track error averages for 1990. These errors range from 30 km at the 0-h forecast period (initial position error) to 567 km at 72 h. The 1990 track errors are less than the previous 10-yr averages at all time periods.

The average 1990 official wind speed forecast errors are listed in Table 4. The forecasts had a negative bias (an underestimate) at all periods, with mean absolute errors increasing with the length of the forecast period.

Acknowledgments. Lixion Avila, Robert Case, Harold Gerrish, and Edward Rappaport contributed to this report. Joan David assisted with the track chart.

REFERENCES